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Radiative characteristics of InAs/InGaAs/InP quantum dot injection lasers

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Introduction

Quantum dot (QD) heterostructures have recently became the subject of the intensive research. Injection lasers with an active region based on InGaAs/AlGaAs QD have shown ultralow threshold current density (J_{th}) [1]. However, the emission wavelength of QDs formed on GaAs substrate is limited by the value of 1.3 μm. It has been previously shown that the QD emission range can be extended up to 2 μm by embedding the InAs QDs into an InGaAs matrix grown on InP substrate [2]. In this work we study threshold, temperature and power characteristics of InAs/InGaAs/InP injection lasers.

1 Experimental methods

The laser heterostructure was grown on n-type InP (100) substrate by solid-source molecular beam epitaxy (MBE). The substrate temperature was 500 °C for the deposition of all layers. Vertically coupled quantum dots (VECODs) were self-organized during the successive deposition of several sheets of QDs. An active region consisted of three InAs QD planes separated by 5-nm-thick InGaAs spacers.

Both four-cleaved facet samples and 100 μm-wide stripe geometry lasers were studied. Laser characteristics were investigated under pulse excitation (1.5 μs pulse duration, pulse interval equals to 100) in the 77–300 K temperature range. InSb photodiode was used for the optical signal registration. Using of different approaches described previously [3, 4] allows us to investigate both spontaneous and stimulated emission in the wide pumping current density range.

2 Results and discussion

An investigation of electroluminescence of four-cleaved facet samples shows the threshold current density as low as 11 A/cm^2 and the lasing wavelength 1.894 μm at 77 K. To our knowledge, this is the lowest J_{th} for a QD injection laser have ever reported before. The linear dependence of the lasing wavelength vs. temperature (Fig. 1) clearly indicates the conservation of the lasing mechanism in the 77-200 K temperature interval. No lasing was observed over 200 K.

The threshold current density of stripe geometry lasers as a function of radiative output losses at 77 K is shown in Fig. 2. It is seen that there is a sharp superlinear growth of the threshold current density with increasing losses. Similar behavior of the J_{th} has been observed in InAs/GaAs QD lasers before. Those heterostructures were grown by MBE as well and had a single sheet of QDs in an active region [5]. We think that the main reason for such drastic increasing of the J_{th} is the gain saturation

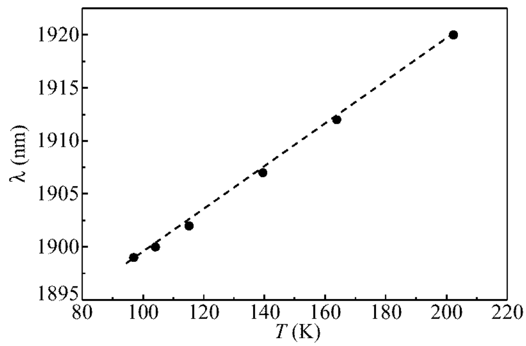

Fig 1. Temperature dependence of the lasing wavelength.

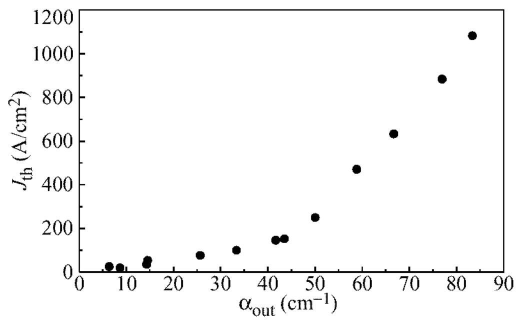

Fig 2. Threshold current density versus radiative output losses.

in QDs. To all appearances it is typical for QD lasers having a few sheets of QDs (no more than 3) in an active region. For example, the gain saturation was observed earlier in (In,Ga)As/GaAs injection lasers grown by MOCVD and that heterostructure had a single sheet of QDs [6].

Figure 3 shows that at 77 K only 40% of carriers take part in the stimulated emission. It is very good result for the first QD lasers in InAs/InGaAs/InP system.

The dependence of the lasing wavelength vs. threshold current density is shown in Fig. 4. There are two pronounced parts in it. These results are in good agreement with the J_{th} dependence vs. radiative output losses (Fig. 2). We believe that there are two mechanisms by which the recombination is realized. The output losses interval of approximately from 50 cm^{-1} to 60 cm^{-1} (it corresponds to the laser cavity length range from 210 μm to 175 μm and J_{th} from 250 A/cm^2 to 450 A/cm^2, respectively) is crucial with a view of the change of lasing mechanism. Electroluminescent investigation of the

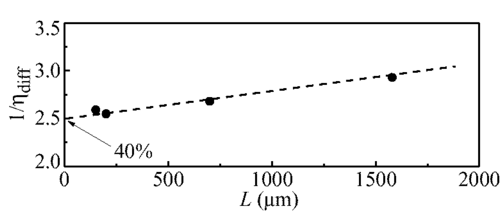

Fig 3. Dependence of the inverse differential quantum efficiency of stimulated emission versus laser cavity length.

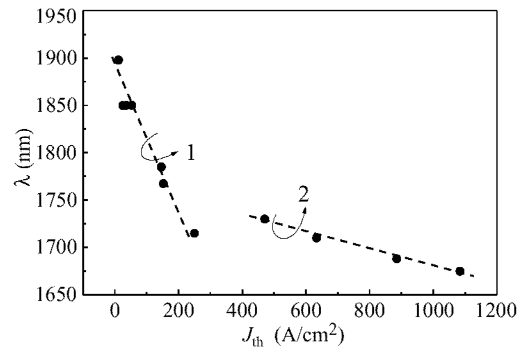

Fig 4. Dependence of the lasing wavelength versus threshold current density.

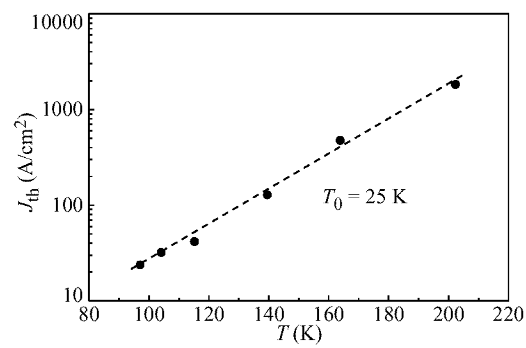

Fig 5. Temperature dependence of the threshold current density.

stripe geometry lasers shows that the stimulated radiative recombination goes via QD states only for the laser cavity length (L) more than 200 μm. Dot line of Fig. 4 marked "1" corresponds to this case. A further decrease in the L leads to the gain saturation via the states of QDs. Lasing switches to higher states. It can be both excited states of QDs and states of the wetting layer. Less wavelength relates to lasing via those states. Dot line of Fig. 4 marked "2" corresponds to it.

The dependence of the threshold current density vs. temperature is shown in Fig. 5. In the temperature range of 77-200 K the J_{th} varies very significantly and is described by the characteristic temperature $T_0 = 25$ K. Sudden increase of the threshold current density was also observed earlier [6] and is caused by thermal evaporation of carriers from QD states to the adjacent layer which makes it necessary to increase the injection current density required to maintain the given gain. Moreover, an increase in the temperature from 77 K to 150 K reduces the radiative spontaneous recombination rate by the factor of 3. In addition, Fig. 6 shows that the same rise of the temperature leads to the decrease of differential quantum efficiency of stimulated emission by the factor of 4. So, main reasons for the characteristic temperature's low value are the non-radiative recombination and the carrier escape from QD states.

3 Conclusions

The possibility of the achievement of the threshold current density as low as 11 A/cm^2 at 77 K in lasers based on InAs/InGaAs/InP has been shown. Lasing wavelength

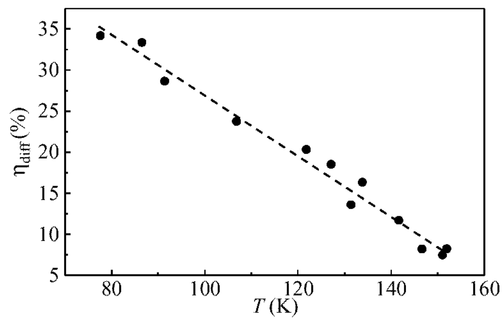

Fig 6. Temperature dependence of the differential quantum efficiency.

reached 1.894 μm. It was found out that there were several causes preventing lasing at the higher temperatures (more than 200 K). The non-radiative recombination and the carrier escape have been studied. The improvement of the QD laser heterostructure‘s crystal perfection and the increase of the number of QD‘s sheets in an active region embedded into a wider bandgap matrix must lead to low threshold lasing via the states of QD at room temperature.

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